Technical Publication No. 68 December, 1948

VARIATIONS IN THE DECAY RESISTANCE OF WHITE OAK

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COMMONWEALTH MYCOLOGICAL INSTITUTE
31 JUL 1964

Vol. XXI No. 1-b

Bulletin of the New York State College of Forestry at Syracuse University

Published quarterly by the New York State College of Forestry at Syracuse, N. Y. Entered as second-class matter, October 18, 1927, at the Post Office at Syracuse, N. Y., under Act of August 24, 1912.

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VARIATIONS IN THE DECAY RESISTANCE OF WHITE OAK

BY

ROBERT A. ZABEL[1]

PART I

INTRODUCTION

The efficient utilization of our national timber resources is becoming more important as the supply diminishes. A more judicious use of the remaining wood supply can be aided materially by additional information on the resistance of wood to decay. It is well known that great variations occur in the decay resistance[2] of wood from different genera and species. There are also variations in decay resistance according to radial position in the stem as shown by recent studies on black locust (40), European larch (12), redwood (43), western red cedar (11), and white oak (39). Such information enables the user to select the more resistant portions of these species for special uses where the decay hazard may be high.

Studies on the chemical and physical properties of wood in relation to its resistance to decay are necessary to understand the protective mechanisms involved in these naturally durable wood substances, and the reasons for their variation. Such data, aside from a general scientific interest, have possible values in future preservative processes. They also have further significance, since certain physical properties of wood can be controlled by silvicultural methods (35). In addition, such studies may reveal a simple test procedure or an easily determined factor that can be used to measure relative decay-resistance within a species.

Chemical studies on many decay resistant species of wood have indicated that their durabilities may be explained largely on the basis of the toxicity of the hot-water extractives. Studies on the distribution of these hot-water extractives in redwood (43), western red cedar (11), and black locust (40) have shown that the outer heartwood contains more hot-water extractives than the inner heartwood, and that this difference is correlated closely with greater durability.

Decay tests (39) on the principal commercial species of oak show that the outer portion of the heartwood is more durable than the

[1] The writer wishes to express his appreciation to Dr. R. R. Hirt for suggesting the project and for guidance during the course of this investigation, to Dr. T. C. Scheffer for suggestions and criticisms, and to Dr. Edwin C. Jahn for advice in the chemical problems involved.

[2] In this paper the terms *decay resistance* and *wood durability* are considered to be synonyms.

inner. If decay resistance in this species can be explained largely on the basis of the toxicity of the hot-water extractives (24), then considerable variation should occur in the amounts or toxicities of these materials across the radius in order to account for the varying radial durability reported. Although no experimental work was done it has been reported (2, 37, 48), that the decay resistance of oaks is due probably to the presence of tannins in the wood. If this is true, then significant amounts of tannin should be present in the extractives of oak and their removal should diminish markedly the toxicity of the extractives.

The present study of the durability of white oak (*Quercus alba* L.) in relation to chemical and physical properties of the wood was undertaken to determine what properties in this species are most closely correlated with decay resistance. White oak was chosen because of its importance in wood industries and its reputation as a durable wood (9).

The specific objectives in this study were, therefore:

1. To determine if a radial durability gradient exists in three white oaks selected as sample material from widely separated localities in New York.
2. To determine the relationship of the following physical and chemical properties to the decay resistance of the heartwood; specific gravity; number of compound rays per half-inch; number of rings per half-inch; age of heartwood; amount of tannin; amount of the hot-water extractives; and pH of the hot-water extractives.
3. To determine the toxicity of various concentrations of the extractives to a common hardwood-destroying fungus.
4. To determine if the toxicity of the extractives in equal concentrations varies with radial position in the stem.
5. To determine whether the removal of the tannins affects the toxicity of extractives.

THE BASIC FACTORS AFFECTING DECAY RESISTANCE

Wood decay, as used in this paper, is defined as those chemical and physical changes in wood that are caused by the activities of a fungus. A wood-destroying fungus must have certain requisites in order to cause decay, namely, suitable temperatures and sufficient amounts of water, oxygen, and food. The natural resistance of wood to decay results when some property of the wood adversely affects one or more of these fungal requisites. The properties of the wood which affect fungal growth can be grouped conveniently into two categories, physical properties and chemical properties.

Reports in the literature on the relationship between various wood properties and decay resistance are summarized and discussed under the following general headings: physical properties, which include position of wood in the stem; and chemical properties, which include extraneous nitrogenous materials and tannins.

PHYSICAL PROPERTIES

Specific gravity, rings per inch, and percent summerwood.—The first important study on wood durability in relation to its various physical properties was done by Zeller (51) on 3 species of southern yellow pine. He found that high specific gravity, an increase in the percentage of summerwood, and a large number of rings per inch were correlated with greater durability in the heartwood. Buckman (10) analyzed Zeller's data and concluded that his results were not justified. Garren (22) reported on the relationship between specific gravity and the rate of decay in loblolly pine sapwood. He found that the higher the specific gravity of a piece of loblolly pine sapwood, the more resistant it was to decay. In defense of his original determinations on the relationship between specific gravity and decay resistance, Zeller (52) agreed with Garren's conclusions and stated that, ". . . the higher the specific gravity of normally grown pine wood, the more resistant it will be to decay by fungi."

Schmitz and Daniels (41) conducted a study on the relative durability of many important western coniferous woods and clearly showed that when different genera are considered, the specific gravity of the wood is not necessarily an indication of its durability. Specific gravity was shown by Scheffer (40) to be little if at all related to differences in the decay resistance of black locust. Southam and Ehrlich (44) also concluded that there was no relationship with specific gravity and decay resistance in western red cedar. In addition, they found ring frequency to be of no value as an index of decay resistance.

Thus, it is evident that no general relationship exists between specific gravity and decay resistance for all woods. However, it should be noted that the lack of this relationship occurs principally in the very durable species, such as western red cedar and black locust, and that a direct relationship has been reported for less durable woods, such as the heartwood of 3 southern pines and the sapwood of loblolly pine. The possibility exists that any effect of specific gravity on decay resistance is masked in the highly durable species by other more important factors such as toxicity of extraneous cell materials.

There are several mechanisms whereby specific gravity might affect wood resistance appreciably by controlling such factors as: air volume, number of resin canals in the summerwood, and various ratios of chemical constituents in the summerwood and springwood.

Position in stem.—The first published results on the relation of position of wood in the stem to durability are found in Zeller's (51) original report. He found no relationship between position in the stem and the durability of 3 species of southern pines.

Sherrard and Kurth (43) showed that both vertical and horizontal position in the stem were related to durability in virgin-growth redwood trees. The most decay-resistant wood was found in the outer heartwood of the butt log. From studies on black

locust, Hopp and Hirt (26) concluded that there is a significant difference in durability associated with radial position in the heartwood. In studies on the decay resistance of western red cedar (11) and European larch (12), Cartwright reported that the most recently formed heartwood was the most resistant and the resistance decreased toward the center of the tree. Scheffer *et al.* (40), studying the relation between the hot-water extractives and decay resistance in black locust, showed that substantial differences in wood durability exist between different radial positions within the same tree.

As a result of decay studies on commercial species of oak, Scheffer (39) found that heartwood from the upper logs was somewhat more resistant than that from the lower logs, and that the outer heartwood was more resistant than the inner. Baxter (6) has shown that wood from the butt of northern white cedar is less resistant to decay by *Poria subacida* than wood from other sections of the trunk.

In summary, no general relationship exists between durability and position of the wood in the stem for all woods. However, outer portions of the heartwood were found to be more durable for the following species: redwood, black locust, western red cedar, and species of oak. In the oaks, durability was found to increase with height, whereas in western red cedar the reverse was true. Position in the stem is an empirical factor and it, in some way, controls other factors, such as: age, rings per inch, specific gravity, amount of extractives, and toxicity of the extractives.

CHEMICAL PROPERTIES

Wood extractives.—Important studies of the relation between the chemical composition of wood and durability were reported by Hawley *et al.* (24). Their work on the water extractives from many durable woods showed that wood durabilities could be explained largely by the toxicity of the water extractives. In all cases the hot-water extractives were more toxic than the cold-water extractives and the heartwood extractives were more toxic than the sapwood extractives within a species. On the basis of the latter statement, they explained the striking difference between the durability of the heartwood and sapwood of durable woods. Sowder (45) tested the effect of kiln temperatures on the durability of western red cedar. His results on the toxicity of hot- and cold-water extractives of heartwood and sapwood were in accordance with the results of Hawley *et al.* The toxicity of extractives from western yellow pine were tested by Anderson (1). He also found the hot-water extractives of the heartwood to be more toxic than the cold-water extractives, but found no pronounced difference in cold-water extractives of heartwood and sapwood. In decay tests on several species Migita (32) found that the durability of *Castanea sp.* was related to the toxicity of its hot-water extractives.

Dadswell and Dadswell (14) studied the toxicity of various fractions of aqueous and alcoholic extractives of the cypress pines (*Callitris sp.*). Toxicity tests showed that the resistant properties

of these woods were due to the presence of a volatile acid and a resinous material. In studies on the distribution of extractives in redwood and their relation to durability Sherrard and Kurth (43) showed that the greater amounts of the extractives were present in the more durable portions of the wood. Service tests substantiated the results of their toxicity studies. They concluded that the durability of redwood was due to the nature of the extractive and that it varied with its distribution. In a study on two black locust trees Hopp and Hirt (26) found that the greater durabilities between positions were more closely associated with the greater amounts of hot-water extractives than with cold-water extractives. They suggested the possibility of using the concentration of hot-water extractives in a tree as an index of decay resistance. Cartwright (11) found a relationship between durability and amount of hot-water extractives in western red cedar. The more durable wood was found to contain the greater amounts of extractives. The pH of the hot-water extractives was taken and in all cases the value was fairly uniform and was not affected by amount of extractive.

Scheffer *et al.* (40), reported on the relation between the hot-water extractives of black locust wood and decay resistance. The results showed that the amount of hot-water extractives was approximately proportional to the decay resistance, and this held true, to a lesser degree, for the toxicity of the extractives. While the amount of hot-water extractives in the wood accounts for resistance to decay radially within an individual tree, it does not account for differences in durability between trees. They explained this by suggesting that the toxic composition of the extractives was uniform within a tree but not between different trees, and that the toxicity of the extractives was not as closely correlated to decay resistance as was the amount of extractives. They concluded that neither extractive content nor its toxicity, as measured by fungal retardation in artificial culture, were adequate for determining relative durabilities of the strains within a species.

To summarize, the toxic nature of the chemical substances in the extractives was shown to bear a close relation to wood durability in many of the very durable woods. Studies on durable woods have shown clearly that the concentration of the extractive varied with radial position. However, the total effectiveness of hot-water extractives in inhibiting fungal growth must be the result of both concentration and toxicity. No previous studies have considered that the toxicity of the hot-water extractives might vary with radial position. Other workers have concentrated the extractive and conducted toxicity tests for various positions, but in all cases the amount of extractive also varied. These toxicity tests measure the combined effect of both toxicity and amount of hot-water extractives with position. To determine the relative toxicity of extractives from various positions in the stem, the extractives have to be evaporated to equivalent concentrations and then tested.

Nitrogen content.—Findlay (18) studied the effect of nitrogen

content on the durability of wood. He reported that various concentrations of ammonium nitrate caused very slight increases in the decay of spruce wood while treatments of Sitka spruce with organic sources of nitrogen caused large increases in decay of wood.

Schmitz and Kaufert (42) studied the relation of asparagine and ammonium nitrate to wood durability. They found that asparagine increased the decay rate of several woods whereas, with one exception, the addition of ammonium nitrate to the woods tested did not cause any significant increase in decay rate. In a study of the relation of urea and various ammonium compounds to wood decay Kaufert and Behr (27) concluded that the susceptibility to decay of sapwood of southern pine, and heartwood of Douglas fir and red oak was not significantly altered by the presence of small amounts of urea, ammonium sulphate, and ammonium phosphate. Asparagine and peptone in small concentrations increased the decay rate of southern pine sapwood and red oak heartwood. However, they doubted the practical significance of these small increases in decay.

In summary, the results of Kaufert and Behr suggest that while nitrogen may affect durability to some degree, undoubtedly other factors play a much more important part.

Tannins.—It is generally believed that the presence of tannins in wood increases its resistance to decay (2, 20, 37, 48). This idea, in all probability, has risen from the observation of two general facts. First, that many durable woods contain considerable amounts of tannin, *e.g.*, chestnut, oaks, black locust, osage orange, quebracho, and red mulberry (2, 48); whereas, many of the non-durable woods such as maple, red alder, and birch contain only small quantities of extractives. Second, the heartwood in many of the durable species contains much larger amounts of tannin than the sapwood (48).

The following summary of information as reported in the literature suggests that tannins may have an important toxic action on fungi.

Cook and Taubenhaus (13) reported the results of extensive tests on the toxicity of a tannin to many fungi. Their results, based on cultural tests, show that tannin retarded growth of many fungi. In order to determine whether toxicity of tannins was caused by tannin or the tannic acid radical, they tested the toxicity of sodium tannates and found these to be only slightly less toxic than tannin.

Lutz (29, 30) in studies on the biologic role of tannin in the plants suggested a mechanism whereby tannins may inhibit fungal growth. He stated that the tannin not only played the role of a more easily oxidized compound but also had a specific action in lowering the activities of oxidase. He suggested that the antioxidant power was the principal biological role of tannins. He (30) also pointed out that, whereas oak was not normally attacked by *Ungulina betulina* [*Polyporus betulinus*] it became susceptible

when part of its tannin content had been removed by soaking in water at 120° C.

Sherrard and Kurth (43) in studies on extracts from redwood found the aqueous tannin extract to be toxic to wood-destroying organisms. Kurth (48) suggested that the tannins acted as anti-oxidants and also that they resisted the attack of wood-destroying fungi. Davidson *et al.* (15), found low concentrations of gallic and tannic acid to be toxic to many fungi.

Henry (16) in studies on the distribution of tannin in oak found the greatest concentrations in the outer layers of the heartwood and that they ranged in amount from 6.0 to 10.0 percent. The tannin content diminished more or less regularly toward the pith, and the sapwood contained the lowest amount, generally from 1.0 to 3.0 percent. Frey and Leinbach (21) made an analysis of tannin content in chestnut, and reported an increase of 100 percent in the tannin content when taken from pith through the outer heartwood. In studies of the influence of temperature on leaching of oak wood Pavlovich (36) determined that the optimum temperature for extraction of the tannin was from 90° to 100°C.

In summary, the high tannin content of many durable species suggests a relationship between tannin content and durability. The strong anti-oxidant power of tannins, their effect on enzymes, and their toxicity to many fungi in culture, further indicates the possibility that they may be related to the durability of some woods. Additional evidence is that in oak the tannin content is greater in the outer portions of the heartwood, a fact which agrees with reports of increased durability in these portions.

This information indicates that the tannins may play an important role in the resistance of oak wood to decay. However, to the writer's knowledge, no published proof exists as to the nature of the toxic material which gives white oak its decay resistance.

PART II

THE DETERMINATION OF THE RADIAL VARIATIONS IN DECAY RESISTANCE OF WHITE OAK

MATERIALS AND METHODS

Trees selected.—Three white oak trees of approximately the same diameter and occupying dominant positions in a white oak forest type (25) in different areas of New York State were selected for study. Information regarding these trees is summarized in Table 1. The 3 trees are designated hereafter in this paper as W1, W2, and W3.

TABLE 1.— DESCRIPTIVE DATA OF THE THREE WHITE OAK TREES USED IN THE DECAY RESISTANCE STUDIES

Serial numbers of the trees	Location	Age in years	D. B. H. in inches	D. B. H heartwood cylinder in inches	Clear length of bole in feet
W1	Cooperstown	120	14.0	11.7	30
W2	Syracuse	130	14.5	12.2	20
W3	Richford	85	14.5	10.0	16

Preparation of test blocks.—The trees were felled in June and two-foot sections of the trunk, at the d.b.h. level, were immediately removed. The top surface of each of these sections was 4.5 feet above the ground line. Two radii at right angles to one another were marked on the top surface of each of the 3 sections and were chosen so as to include a short and a long radius. These radii were removed in board form, planed to a uniform thickness, and sawed into blocks approximately one-half inch square at the ends and one inch in length. The individual test blocks of each radius were marked for identification according to position and level (Fig. 1). The pith-containing block at each level was common to both a long and a short radius. The remaining block positions were established in consecutive order at one-half-inch units from the pith block through to the cambium.

Block equilibrium weight.—Loss in weight due to decay under controlled conditions was used as an index of the decay resistance of the wood. To determine the loss in weight due to decay it is necessary to establish an equilibrium weight for each test block, before and after exposure to the decay-causing organisms. In obtaining the equilibrium weights of the blocks it was desirable to approximate oven-dry weight values for simplicity in specific gravity calculations and yet to avoid the deleterious effects of prolonged high temperature on the decay resistance (49) of the test blocks. For these reasons the equilibrium weights of the blocks were established in desiccators containing P_2O_5 and kept at 45° C., a value which probably does not exceed the temperature that wood of white oak is ordinarily exposed to during service. This procedure brought the blocks to a moisture content equilibrium value within one percent of that obtained by oven drying a series of check blocks at 102° C.

The equilibrium weight of a block was considered to be a constant when there was no variation in 3 successive daily weighings. All final weighings were completed within 30 seconds per block

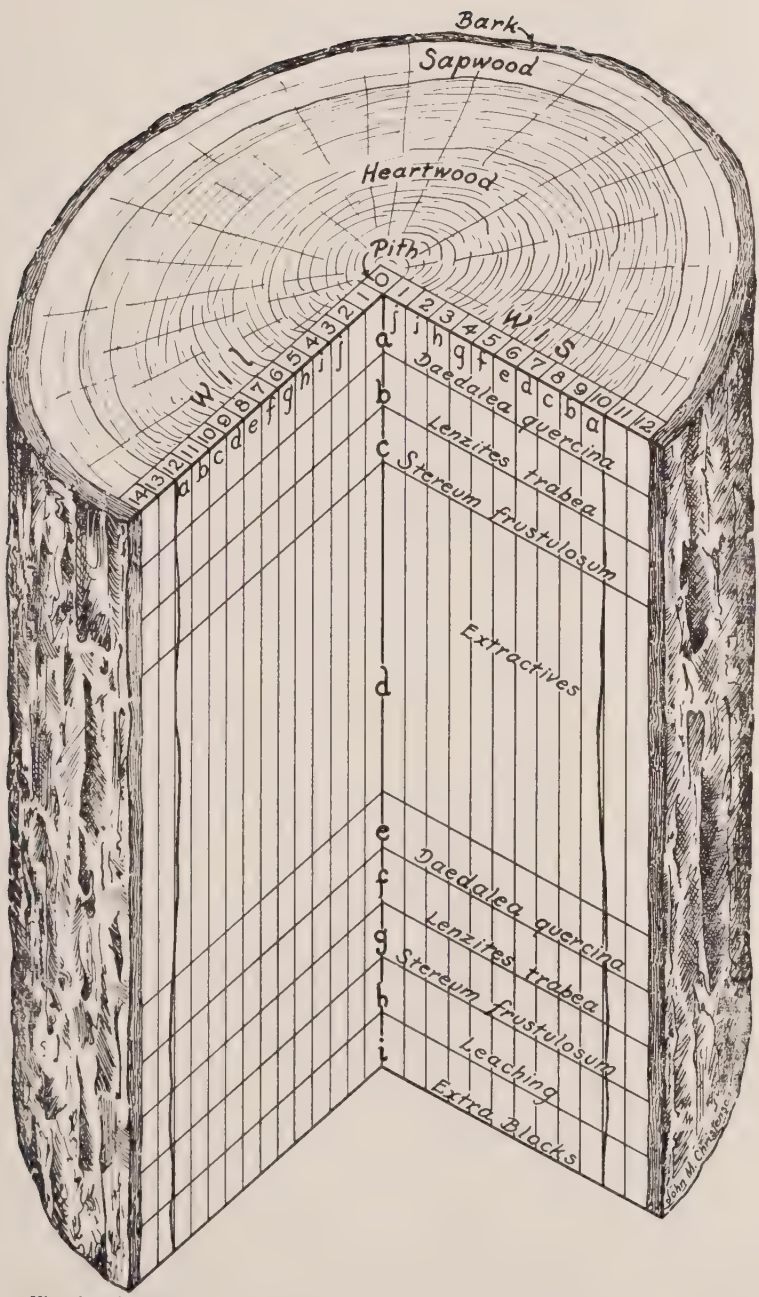

Fig. 1.—A section of an oak stem showing the position of the blocks selected for the study.

because under room conditions blocks picked up moisture from the atmosphere at a rate of approximately 0.6 mg. per minute. This procedure eliminated the necessity of weighing bottles for each block and kept the accuracy level well within one-half of one percent.

Sterilization of test blocks.—When the equilibrium weights were established the surfaces of the blocks were sterilized by placing each test block in a Petri dish and submitting it to steam at 100° C. for 15 minutes without pressure. The blocks were left in the Petri dishes to cool within the saturated atmosphere of the autoclave for 12 hours. This procedure sterilized the blocks and aseptically added approximately 10 percent moisture to each.

Fungi used.—Three different fungi, *Daedalea quercina* (L.) Fries, *Stereum frustulosum* (Pers.) Fries and *Lenzites trabea* (Pers.) Fries were selected as decay agents. The first 2 fungi occur commonly on oak and cause a brown cubical rot and a white pocket rot respectively (7). *L. trabea* causes a brown cubical rot in many coniferous and non-coniferous woods (7, 28). Each of these fungi produced an abundance of aerial mycelium in culture which is a very desirable characteristic in acquiring uniform contact of the mycelium with the decay blocks for the particular type of tests that were made.

Decay chambers.—Small square-sided bottles with a capacity of 6 ounces were used as decay chambers for the individual blocks. The bottles were placed in a horizontal position and 21 ml. of 2 percent malt agar were added to each culture bottle. After the agar was sterilized and had hardened, a small V-shaped piece of glass tubing was placed on the surface of the agar in each bottle as a support for the oak block which was to be added later. The fungi were then planted on the agar of the respective bottles. The cultures were allowed to incubate for 3 weeks and then the test blocks were placed on the glass supports with their tangential surface toward the mycelium. The blocks picked up moisture rapidly. Within 3 days all the blocks were held firmly by the mycelium and the decay chambers could be moved without disturbing the blocks. Previous tests showed that the blocks absorbed sufficient moisture within one week so that decay could begin.

The decay chambers were placed on shelves in a thermostatically controlled dark decay cellar where the temperature was kept at 30° C. A high humidity was maintained in the decay cellar throughout the decay period to retard the drying of the agar in the chambers.

Since white oak is relatively decay resistant (9, 50) the cultures were incubated for 4 months in order to obtain measurable losses in weight. This time interval was determined by means of control blocks which were removed and examined for decay each month.

Determining weight loss.—At the end of the 4-month decay period the blocks were removed from the decay chambers, cleaned

of all surface mycelium, and placed in desiccators under similar conditions previously employed for determining the original equilibrium weights. The losses in weight per block were expressed as a percent of the original block weight at equilibrium.

RESULTS

The percent-weight-loss of the blocks, classified according to position in the stem, tree, and fungus are presented in Tables 2, 3, and 4.

Check blocks, although not included in the tables, were subjected to all the conditions of the test blocks except contact with a fungus. No weight loss or gain occurred.

The heartwood radii of the trees W1, W2, and W3 (Tables 2, 3, and 4), were of different lengths and therefore when subdivided into the test blocks the radii did not always contain the same number of positions. Graphical studies of weight losses for the long and short heartwood radii per tree indicated that the trends were quantitatively similar. It was assumed that in the long and short radii the weight loss was uniform within each block. Those radii with more or less than 10 positions per heartwood radii were proportioned to 10 positions. The pith blocks were excluded since they were common to both kinds of radii. Although the pith and sapwood blocks are not considered in the simple statistical analysis of the data, they are placed in the tables and graphs for comparative purposes.

The proportioned weight losses for the long and short radii, classified according to position, tree, and fungus, are presented in Tables 5, 6, and 7.

Graphical presentations of the calculated weight-loss for the positions in each tree, and for all trees according to the fungus used, are given in Figures 2, 3, 4, and 5.

These data (Tables 2 to 7, Fig. 2 to 5) indicate that there is great variation in the decay resistance of white oak wood from various radial positions in the stem. Uniform heartwood durability gradients with radial position in the stem are apparent when the mean weight losses for the 3 trees are combined (Fig. 5). In all trees the most decay resistant wood was found in the outer heartwood zones adjacent to the sapwood. The least durable heartwood in all trees was located in the pith region. In fact, two of the fungi, *Daedalea quercina* and *Stereum frustulosum*, caused greater weight losses in the pith position of the heartwood than in the sapwood. The data indicate that the outer heartwood is in most cases at least twice as durable as heartwood obtained from the center of the tree.

The resistance of the heartwood to decay varied with the test fungi. The fungus, *Lenzites trabea*, which is least common on oak, caused the smallest amount of decay, whereas *S. frustulosum* which is very common on oak caused the greatest amount of decay. In general the durability gradient within the heartwood retained the same form for all the fungi used.

TABLE 2.— THE PERCENT-WEIGHT-LOSS OF THE TEST BLOCKS FOR EACH RADIAL POSITION IN TREE W1

Fungi	Radii	Position of blocks in the radius												
		0	1	2	3	4	5	6	7	8	9	10	11	12	13
Daedalea quercina	w1sa	36 2	9 8	8.3	9.8	9 1	9 4	9.0	7 4	5.2	7.8	3 9	13 2[a]	....	....
" "	w1se	15 0	9 2	8.3	9 5	9 3	9.5	8.4	6.8	8.5	7.6	4 5	11 2	12.9	....
" "	w1la	36.2	11.1	9.7	8.8	9.9	10.0	9.4	8.7	9.8	8.4	5.6	4.2	6.6	7.1
" "	w1lc	15 0	10 6	10.0	10 4	11.0	10.4	10.1	6.3	6.5	8.5	7 2	7.6	6.3	12.1
Lenzites trabea	w1sb	19.1	12.5	8 2	9 3	6.7	4 5	7.0	5 0	6 7	5.0	1.1	7 7	23.8	....
" "	w1sf	19.5	12.1	11.8	12.6	10.1	6.3	4.7	4.6	7.0	2.2	1.8	7.3	17.3	....
" "	w1lb	19 1	15 8	12 0	13 6	9.7	9.1	6 9	6 6	7 4	5 6	5 0	2.2	1 1	13.4
" "	w1lf	19 5	13 3	12 6	12.2	13 5	8.6	6 8	5 9	6.6	6.2	6.6	4.5	0.6	7.8
Stereum frustulosum	w1sc	26 5	28.3	25 6	22 7	20.2	21.1	19.1	20.0	18.3	18 1	9.7	13.5	12.6	....
" "	w1sg	25 7	21 9	26 1	23 7	18 0	22 2	22.6	21.3	20.4	19.7	14.7	19.3	14.8	....
" "	w1le	26 5	29.8	15.5	19 1	22.5	22.1	22.4	19.6	18.7	18 7	17.8	17.5	11.4	13.6
" "	w1lg	25 7	26.9	23 4	13.7	22 8	22 5	22.6	21.0	18.5	19.2	18.6	17 0	15.8	10.4

[a] The test blocks to the right of the heavy line are sapwood.

TABLE 3. THE PERCENT-WEIGHT-LOSS OF THE TEST BLOCKS FOR EACH RADIAL POSITION IN TREE W2

Fungi	Radii	Position of blocks in the radius													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Daedalea quercina	w2sa	8 3	6 4	4 7	7 9	6 6	5 1	..	6 5	4 0	5 5	10 4[a]	21 8	....	...
" "	w2se	9.4	7.6	9.4	6.4	7.4	5.6	6.7	7.1	5.6	6.6	9.8	23.4	....	...
" " ...	w2la	5 7	8 0	7 1	7.0	3 0	4 4	3 6	3.4	4 7	3 4	1 9	1 4	4 8	18 7
" "	w2le	8 7	8 8	8 2	7 1	4 6	4 3	0 9	1 8	5 1	5 1	1 9	3 2	2 8	13 0
Lenzites trabea	w2sb	9 2	3 5	0 0	0 0	0 0	0 4	0 8	0.8	0 0	2 2	12 1	26 4	...	...
" "	w2sf	8 7	4.8	0.0	0 0	5 1	0 0	0 0	0.0	0 0	1 5	12 4	21.1	...	
" "	w2lb	4.1	10 3	0 4	0 0	0 0	0 0	0 4	0.0	0 0	0 0	0 0	0 5	0 0	27 1
" "	w2lf	2 0	7 5	3.2	4 3	1 3	1.0	1.0	0.4	0 0	1 5	0 0	0 5	0 0	12 0
Stereum frustulosum .	w2sc	24 9	10 9	5 8	4.7	5 0	4 2	6.2	6 3	5 9	9 7	14 6	11 0	..	..
" " .	w2sg	24 7	10.5	6 4	4 6	4.8	5.3	5.3	6.6	6 2	7 9	12 2	11 8	....	....
" "	w2le	10.4	12 1	7 5	5.2	3 9	3 4	3 7	3 5	2 9	2 4	3 8	3 4	4 0	8 4
" "	w2lg	19 0	19 9	8 7	5 6	3 6	3 7	3 8	3 7	2 7	2 5	4 3	3 7	4 0	9 8

[a] The test blocks to the right of the heavy line are sapwood.

TABLE 4.— THE PERCENT-WEIGHT-LOSS OF THE TEST BLOCKS FOR EACH RADIAL POSITION IN TREE W3

Fungi	Radii	Position of blocks in the radius													
		0	1	2	3	4	5	6	7	8	9	10	11	12	13
Daedalea quercina	w3sa	25.6	8 2	7 7	7 2	4 9	6 4	4 7	4 0	6 2	5 4	12 4[a]	7.9	. . .	....
" "	w3se	11.5	....	9 8	6 4	5.8	5.5	4.0	5.7	8 5	5.4	10 4	12.3	0.0	....
" "	w3la	25 6	6 7	5.2	4.8	6 8	4 3	5 2	3.6	4 0	3 4	....	6.3	11.3	0.0
" "	w3le	11.5	8 6	8 2	8 1	9.4	4 6	....	5 2	5 5	3.3	4.4	4.5	8.1	14.5
Lenzites trabea	w3sb	1 3	1 8	4 6	3 8	0 9	....	0.9	0.0	3 7	0 0	3.2	3.5	...	....
" "	w3sf	6.5	3.4	4 5	5.8	3.2	3 9	3.9	2 2	2.2	1 7	4 2	7 7	0.9	....
" "	w3lb	1 3	6 2	6 2	4.2	4 2	3.5	2 2	1.4	0 9	0.4	0 0	3.0	10.6	16.4
" "	w3lf	6.5	4 7	6 1	6 5	5 8	4 8	3.7	1 6	0 0	0.0	0 9	0.8	7.5	20.7
Stereum frustulosum	w3se	21 8	18 9	13 5	18 4	13 0	15 0	9.7	13 5	15 0	10 1	12.2	11.1	....	....
" "	w3sg	21 3	21 4	17.7	18 5	12.8	15.1	18.0	18.7	17 4	19.3	14 2	12.8	16.4	....
" "	w3le	21 8	22 6	19.5	18 6	17 1	16 7	15 6	12 3	14.2	16.3	14.0	9.2	12 7	10 0
" "	w3lg	21 3	15 1	15.2	17 6	17 8	13 0	15 6	15.8	15.6	15 4	9.9	9 2	11.5	18 2

[a]The test blocks to the right of the heavy line are sapwood.

TABLE 5.— THE PERCENT-WEIGHT-LOSS OF THE BLOCKS WHEN EACH RADIUS IS PROPORTIONED INTO TEN EQUAL UNITS IN TREE W1

Fungi	Radii	Position of blocks in the radius									
		1	2	3	4	5	6	7	8	9	10
Daedalea quercina . . .	w1sa	9.8	8.3	9.8	9.1	9.4	9.0	7.4	5.2	7.8	3.9
" " . . .	w1se	9.2	8.3	9.5	9.3	9.5	8.4	6.8	8.5	7.6	4.5
" "	w1la	10.8	9.4	9.3	10.0	9.5	8.8	9.4	7.0	4.6	6.2
" " . . .	w1lc	10.5	10.1	10.7	10.6	10.2	6.3	7.2	7.8	7.4	6.5
Lenzites trabea	w1sb	12.5	8.2	9.3	6.7	4.5	7.0	5.0	6.7	5.0	1.1
" "	w1sf	12.1	11.8	12.6	10.1	6.3	4.7	4.6	7.0	2.2	1.8
" "	w1lb	15.2	12.6	11.7	9.3	7.2	6.8	6.8	5.3	3.2	1.3
" "	w1lf	13.2	12.5	12.8	10.3	7.2	6.0	6.5	6.4	5.3	1.3
Stereum frustulosum .	w1sc	28.3	25.6	22.7	20.2	21.1	19.1	20.0	18.3	18.1	9.7
" " . . .	w1sg	21.9	26.1	23.7	18.0	22.2	22.4	21.3	20.4	19.7	14.7
" " . . .	w1lc	26.8	16.8	20.8	22.2	22.4	19.4	18.7	18.3	17.6	12.3
" " . . .	w1lg	26.4	20.2	18.3	22.6	22.6	20.6	18.7	18.9	17.6	16.0

TABLE 6.— THE PERCENT-WEIGHT-LOSS OF THE BLOCKS WHEN EACH RADIUS IS PROPORTIONED INTO TEN EQUAL UNITS IN TREE W2

Fungi	Radii	Position of blocks in the radius									
		1	2	3	4	5	6	7	8	9	10
Daedalea quercina . . .	w2sa	8.3	6.4	4.7	7.9	6.6	5.1	. . .	6.5	4.0	5.5
" " . . .	w2se	9.4	7.6	9.4	6.4	7.4	5.6	6.7	7.1	5.6	6.6
" " . . .	w2la	6.4	7.6	7.1	3.6	4.1	3.5	4.4	2.9	1.6	4.0
" " . . .	w2le	8.7	8.5	7.5	4.7	3.2	1.5	4.6	4.2	2.6	2.9
Lenzites trabea	w2sb	9.2	3.5	0.0	0.0	0.0	0.4	0.8	0.8	0.0	2.2
" "	w2sf	8.7	4.8	0.0	0.0	5.1	0.0	0.0	0.0	0.0	1.5
" "	w2lb	5.8	5.7	0.1	0.0	0.2	0.2	0.0	0.0	0.3	0.1
" "	w2lf	3.2	5.2	4.0	1.5	1.0	0.6	0 2	1.0	0.2	0.1
Stereum frustulosum .	w2sc	24.9	10.9	5.8	4.7	5.0	4.2	6.2	6.3	5.9	9.7
" " . . .	w2sg	24.7	10.5	6.4	4.6	4.8	5.3	5.3	6.6	6.2	7.9
" " . . .	w2lc	10.8	9.9	5.8	3.9	3.5	3.6	3.0	2 8	3.6	3.8
" " . . .	w2lg	19.2	13.7	6.5	3.8	3.7	3.7	2.9	3.0	4.0	3.9

TABLE 7. THE PERCENT-WEIGHT-LOSS OF THE BLOCKS WHEN EACH RADIUS IS PROPORTIONED INTO TEN EQUAL UNITS IN TREE W3

Fungi	Radii	Position of blocks in the radius									
		1	2	3	4	5	6	7	8	9	10
Daedalea quercina . . .	w3sa	8.2	7.7	7.3	5.7	5.7	5.7	4.5	4.5	6.1	5.4
" " . . .	w3se	. . .	9.8	7.3	6.0	5.7	4.8	4.6	6.3	8.2	5.4
" " . . .	w3la	6.7	5.2	4.8	6.8	4.3	5.2	3.6	4.0	3.4	. . .
" " . . .	w3le	8.5	8.2	8.4	7.7	4.6	5.2	5.4	3.9	4.2	4.4
Lenzites trabea	w3sb	1.8	4.3	4.0	2.0	0.1	0.1	0.6	0.8	3.3	0.0
" "	w3sf	3.4	4.4	5.5	4.1	3.6	3.9	3.3	2.2	2.2	1.7
" "	w3lb	6.2	6.2	4.2	4.2	3.5	2.2	1.4	0.9	0.4	0.0
" "	w3lf	4.9	6.2	6.3	5.4	4.3	2.6	0.6	0.0	0.8	0.8
Stereum frustulosum .	w3sc	18.9	14.1	17.3	14.9	15.0	13.6	11.0	13.8	14.5	10.1
" " . . .	w3sg	21.4	17.7	18.5	12.8	15.1	18.0	18.7	17.4	19.3	14.2
" " . . .	w3lc	22.6	19.5	18.6	17.1	16.7	15.6	12.3	14.2	16.3	14.0
" " . . .	w3lg	15.1	15.6	17.6	16.1	14.2	15.7	15.7	15.5	10.8	9.3

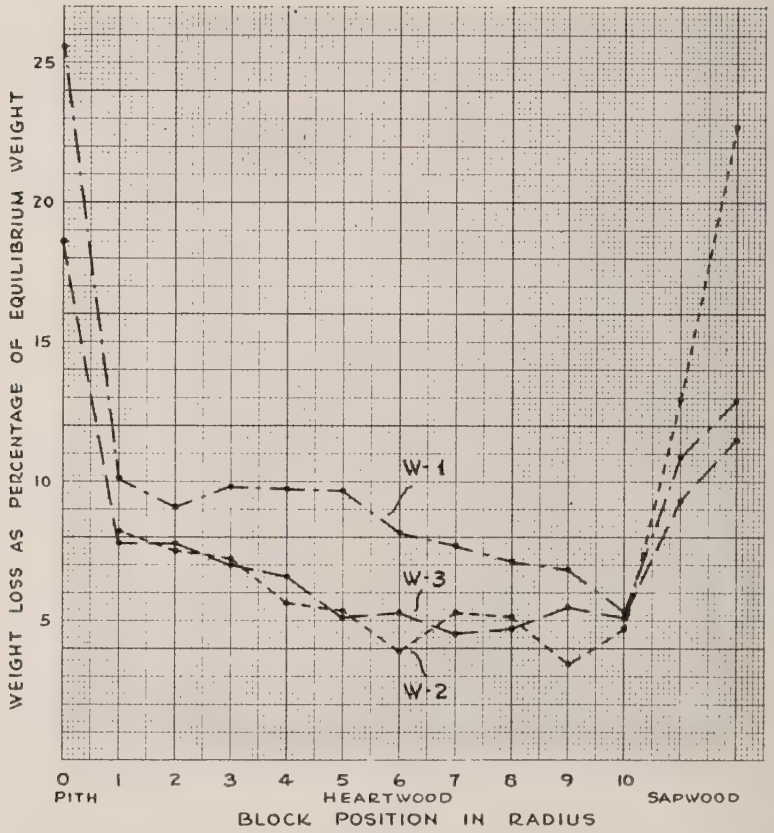

Fig. 2.—The relationships between weight loss and radial position of the blocks for tree W1, W2, and W3 when decayed by *Daedalea quercina*. Each plotted point in the heartwood is the mean of 4 determinations.

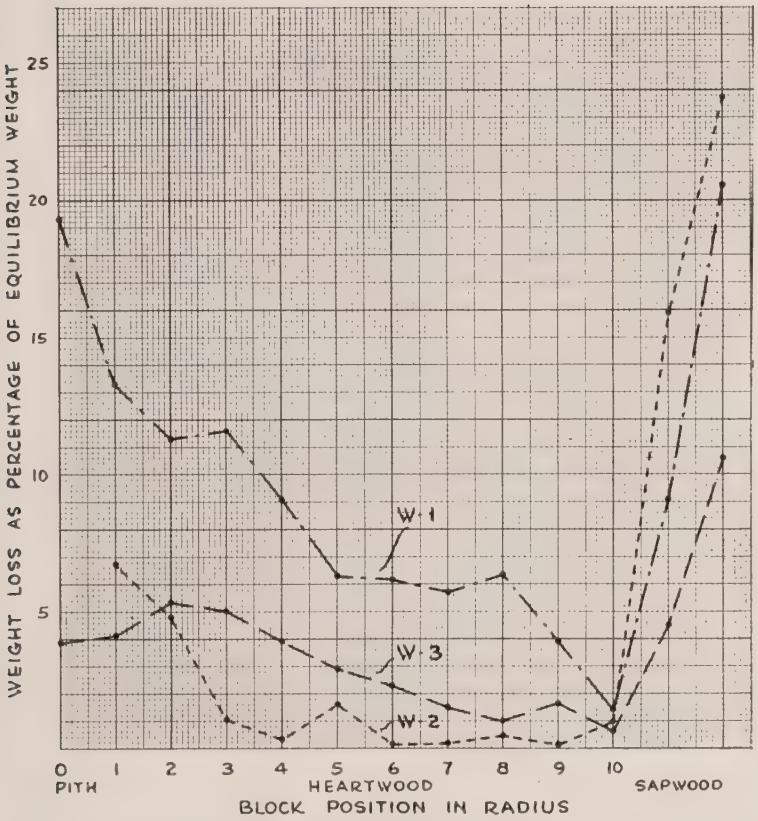

Fig. 3.—The relationships between weight loss and radial position of the blocks for tree W1, W2, and W3 when decayed by *Lenzites trabea*. Each plotted point in the heartwood is the mean of 4 determinations.

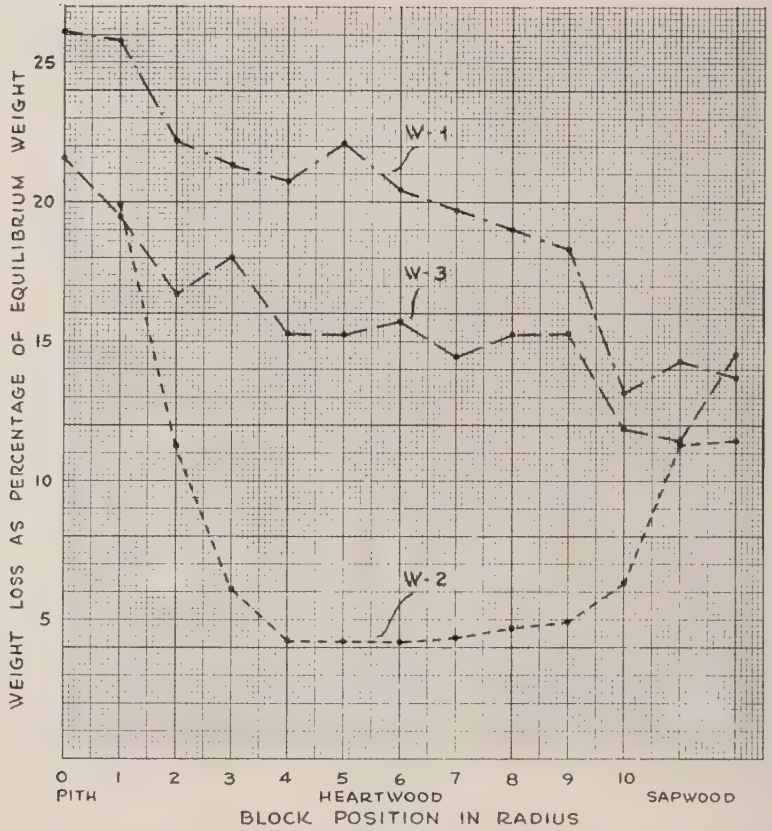

Fig. 4.—The relationships between weight loss and radial position of the blocks for tree W1, W2, and W3 when decayed by *Stereum frustulosum*. Each plotted point in the heartwood is the mean of 4 determinations.

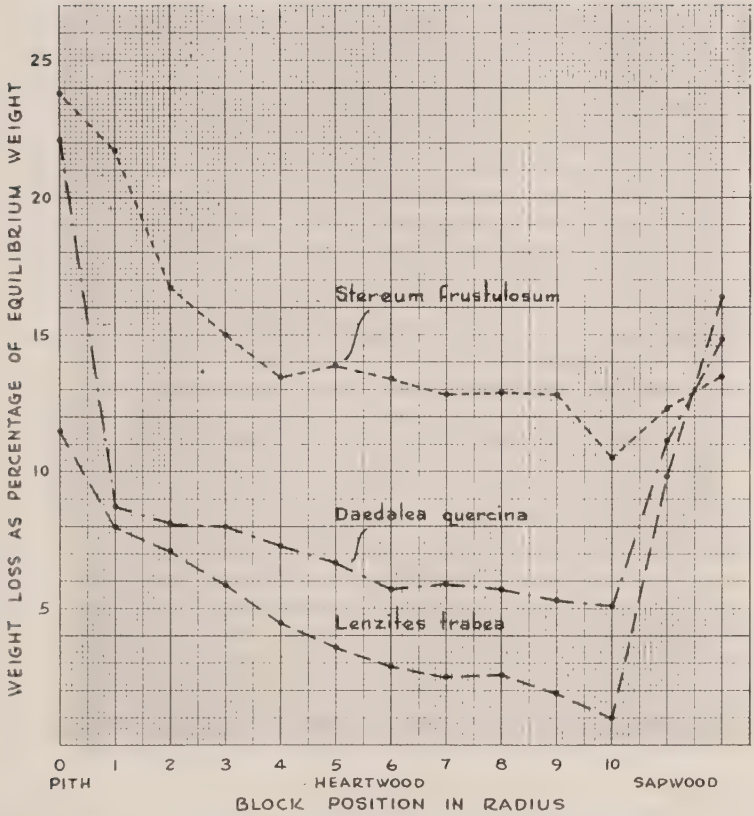

Fig. 5. The relationships between weight loss and radial position of the blocks for the 3 trees combined when decayed by *Daedalea quercina*, *Lenzites trabea*, and *Stereum frustulosum*. Each plotted point in the heartwood is the mean of 12 determinations.

Also, the resistance of the sapwood to decay varied with the test fungi. *L. trabea* and *D. quercina* caused very high sapwood weight losses, whereas *S. frustulosum* caused low sapwood weight losses. The sapwood in the outermost portions of the radius was less durable than that close to the heartwood. This suggests the possibility that in white oak the transformation of sapwood to heartwood begins considerably in advance of the color difference delimiting heartwood and sapwood.

Striking differences in the decay resistance of the 3 trees are apparent. All of the fungi caused the greatest amount of decay in tree W1 and the least in tree W2. Some differences in the durability gradient were apparent between trees. The trend of the gradients in trees W1 and W3 differed from tree W2 (Fig. 2 to 4).

It was considered that the durability gradients were established graphically and in little need of mathematical confirmation or proof. If it is assumed that the relationship between weight loss and position (exclusive of pith and sapwood positions) are linear, calculations indicate that all the correlation coefficients (3, 34) obtained are significant (Table 8). This assumption is valid with the exceptions of curve W2 in Figures 3 and 4 as evidenced by the high correlation coefficients obtained.

TABLE 8.— THE DEGREE OF ASSOCIATION BETWEEN WEIGHT LOSS AND POSITION IN THE RADIUS FOR THE THREE FUNGI AND TREES INDIVIDUALLY AND COLLECTIVELY AS DETERMINED BY CORRELATION COEFFICIENTS.

Fungus	Correlation coefficient			
	W1	W2	W3	W1–W2–W3
Daedalea quercina	−.919**	−.858**	−.847**	−.981**
Lenzites trabea	−.963**	−.726*	−.926**	−.970**
Stereum frustulosum	−.895**	−.634*	−.849**	−.849**

* Significant values (5 percent level).
** Highly significant values (1 percent level).

DISCUSSION AND SUMMARY

The durability of the heartwood in the 3 white oaks varied with radial position (Tables 2 to 7, Fig. 2 to 5). In general, the wood in the outer part of the heartwood cylinder was the most durable and decreased toward the pith. The wood near the pith area was found to be less durable than the sapwood for 2 of the decay fungi.

There are differences in resistance to decay among the 3 white oaks. Of the 3 trees, W1 was the most susceptible to decay, and W2 the most resistant. This same order of relative durability was maintained among the trees for each of the 3 fungi used as decay agents (Fig. 2 to 5).

Stereum frustulosum produced the greatest amount of decay; *Daedalea quercina* less; and *Lenzites trabea* the least.

PART III

RELATION OF CERTAIN CHEMICAL AND PHYSICAL FACTORS TO THE DECAY RESISTANCE OF WHITE OAK

MATERIALS AND METHODS

The data for the physical properties considered in this part of the study were taken from the blocks used in the decay tests. They were obtained before the blocks were exposed to the fungi. The data for the chemical properties were obtained from extractive blocks (Fig. 1).

Previous tests have shown that the durability gradients between the long and short radii are similar. In order to eliminate proportioning of the values from the long radii, only the data obtained from the short radii are considered in this section of the paper. For the extractive and tannin determinations the size of the positions was enlarged radially so that each sample block, excluding the pith block, contained one-fifth of the heartwood radius.

Specific gravity.—The specific gravity determinations are based on the wood equilibrium volumes and weights obtained over P_2O_5 in desiccators at 45° C. Preliminary work showed that blocks under these conditions reached an equilibrium weight that was within 1 percent of that obtained in an oven at 102° C. The slight error incurred in computing a specific gravity by using equilibrium weights and volumes at a 1-percent moisture content are within the accuracy limits of the method and hence may be disregarded. Equilibrium volumes were obtained by measurement to within 0.01 mm. When the blocks were visibly distorted as a result of drying stresses, average dimensions were obtained. All block equilibrium weights were made within 0.01 gm.

Rings per half-inch.—Ring counts were made before the blocks were sawed from the radial boards. On those blocks where only partial rings occurred, the number of summerwood zones were

tabulated. Since each block measured approximately one-half inch radially and tangentially, this unit was used rather than rings per inch.

Rays per half-inch.—Compound rays measured tangentially per half-inch were selected as a unit for the reason just stated. Only the large characteristic compound rays of oak, visible to the unaided eye were tabulated.

Age of heartwood.—Age determinations were made before the blocks were sawed from the radial boards. Age of the wood was determined by counting from the outer heartwood zone to the center of each block.

Amount of hot-water extractives.—Special blocks for each radial position (Fig. 1) were ground in a Wiley mill until the sawdust was fine enough to pass through a medium mesh screen.

The method proposed by Bray (8) was used to obtain the hot-water extractives. The loss in sample weight due to leaching, that is the difference between the calculated oven-dry weight and the leached oven-dry weight, was used to determine the weight of the extractives. All weighings were made to within 0.001 gm. After filtration all the hot-water extractives were kept at 5° C. until used in the toxicity tests.

Hydrogen ion concentration of the hot-water extractives.—All pH determinations were made with a Beckman pH meter (Laboratory Model G). Readings were made to within 0.05 of a pH unit. All determinations were obtained within 24 hours of the time of extraction.

Amount of tannin.[3]—The wood used for the tannin determinations was from the same source as that used in obtaining the hot-water extractives. A modification of the Wilson-Kern method (47) of determining tannin was used since only limited amounts of sawdust were available for the test. Since tannins are soluble in hot water and a temperature of 90°-100° C. is optimum for their removal in oak wood (36), it was assumed that hot-water extractives from the various radial positions would contain most of the tannins. The standard method for obtaining hot-water extractives (8) was altered so as to obtain them in higher concentrations. Two-and-one-half-gram samples of sawdust, of known moisture content, were digested for 3 hours with 50 ml. of distilled water in 200 ml. Erlenmeyer flasks under reflux. The sample was then transferred to a tared Jena and washed with 75 ml. of boiling distilled water. This method when compared against standard procedures removes 95 percent of the hot-water extractives. One and two-tenths grams of hide powder,[4] of known moisture

[3] The term tannin as used in this article is defined as including all those plant materials which precipitate gelatine from an aqueous solution and are capable of combining with skin protein to form leather (48).

[4] The hide powder used in these studies was official hide powder for tannin analysis (Lot No. 22) obtained from Will Corporation, Rochester, N. Y., manufactured by Keystone Tanning and Glue Company, Ridgway, Pa.

content and water-soluble content was added to each of the tannin solutions. The mixtures were agitated for 6 hours, then filtered through tared Jenas. All filtrates were tested for tannins with a solution of 1 percent gelatin and 10 percent NaCl. In all cases the hide powder had removed all the tannin. The hide-tannin complex was washed with distilled water until the wash waters gave negative tests for non-tannins and semi-tannins when a dilute solution of $FeCl_3$ was added. The hide-tannin complex was oven-dried at 102° C. for 18 hours. The increase in weight due to tannin[5] was expressed as a percent of the calculated oven-dry weight of the sawdust sample. All weighings were made to within 0.001 gm. in weighing bottles.

RESULTS

The averages of the physical properties determined for the decay blocks, classified for the 3 trees according to position and the fungus to which the blocks were subjected, are presented in Table 9. The averages of the chemical properties determined for the extractive blocks classified for the 3 trees are presented in Table 10. Simple graphical methods were used to determine the relationships between the various properties and weight loss (Fig. 6 to 11).

[5] It was not possible to run the tannin analysis on the wood samples until 7 years after the felling of the test trees. The tannin content of wood decreases considerably with age (20). Also it was necessary to use lower concentrations of tannin in the solution being analyzed than the standard method recommends (47). For these reasons it is felt that the tannin values obtained are of greater comparative rather than quantitative value.

TABLE 9.— THE RELATIONSHIPS BETWEEN THE PHYSICAL PROPERTIES AND MEAN WEIGHT LOSS PERCENT PER RADIAL POSITION FOR TREES W1, W2, AND W3 COMBINED

Fungi	Physical properties	Means of the various physical properties [a]									
		Position of blocks in radius									
		1	2	3	4	5	6	7	8	9	10
Daedalea quercina	Weight loss percent	9.0	8.0	7.8	7.2	7.5	6.2	6.1	7.0	6.0	5.1
	Specific gravity	0.78	0.81	0.81	0.84	0.79	0.75	0.71	0.73	0.70	0.65
	Rings per half-inch	11.0	7.0	5.7	6.0	6.8	6.5	6.5	5.0	5.5	6.0
	Rays per half-inch	3.5	3.7	3.0	4.0	4.3	3.6	2.8	3.0	4.1	5.0
	Heartwood age	79.0	67.0	59.0	53.0	44.5	37.0	29.0	22.0	15.0	7.0
Lenzites trabea	Weight loss percent	9.2	6.2	....	5.2	4.9	4.1	3.8	3.8	2.2	1.6
	Specific gravity	0.77	0.81	0.82	0.79	0.77	0.75	0.72	0.73	0.70	0.65
	Rings per half-inch	12.0	8.6	6.0	7.0	7.0	7.0	7.0	5.2	5.0	8.5
	Rays per half-inch	3.2	3.1	3.5	4.0	3.8	3.7	4.0	4.0	4.7	5.5
	Heartwood age	83.0	68.0	59.6	55.5	45.6	37.0	26.0	21.4	15.0	10.7
Stereum frustulosum	Weight loss percent	23.3	17.4	15.9	12.2	14.1	13.1	14.2	14.0	13.2	10.5
	Specific gravity	0.78	0.80	0.82	0.80	0.78	0.76	0.73	0.74	0.72	0.65
	Rings per half-inch	10.8	7.9	5.9	6.6	6.5	6.6	6.5	5.1	5.7	8.5
	Rays per half-inch	3.7	4.0	4.0	4.6	4.5	4.1	4.6	4.6	4.5	5.0
	Heartwood age	79.7	68.0	60.5	53.0	45.0	37.3	29.0	21.8	15.5	10.5

[a] Each value is the mean of 6 separate determinations.

TABLE 10.— THE AMOUNT AND pH OF THE HOT-WATER EXTRACTIVES AND THE TANNIN CONTENT OF OAKWOOD AS AFFECTED BY RADIAL POSITION IN TREES W1, W2, AND W3.

Trees	Position of block in radius						
	Pith	2	4	6	8	10	Sapwood
	Average hot-water extractive content (percent)						
W1	4.0[a]	5.1	4.4	4.8	4.8	4.9	5.9
W2	5.3	6.0	7.0	6.3	6.6	6.1	...
W3	6.7	5.1	4.4	4.5	5.4	6.5	5.5
Average	5.3[b]	5.4	5.3	5.2	5.6	5.8	5.7
	Average pH of hot-water extractives						
W1	4.3[a]	4.3	4.2	...	4.1	4.1	4.5
W2	4.1	3.9	3.8	3.8	3.8	3.9	4.6
W3	4.4	4.0	4.0	3.9	3.8	3.9	5.5
Average	4.3[b]	4.1	4.0	3.8	3.9	4.0	4.9
	Average tannin content (percent)						
W1	0.8[a]	1.2	0.9	1.1	1.2	1.1	0.3
W2	1.4	1.3	2.3	2.3	2.6	2.3	0.4
W3	2.0	1.3	1.1	1.0	1.2	1.7	0.4
Average	1.4[b]	1.3	1.4	1.5	1.7	1.7	0.4

[a] Each value classified by individual trees is the mean of 2 separate determinations.
[b] Each value classified for the three trees is the mean of 6 separate determinations.

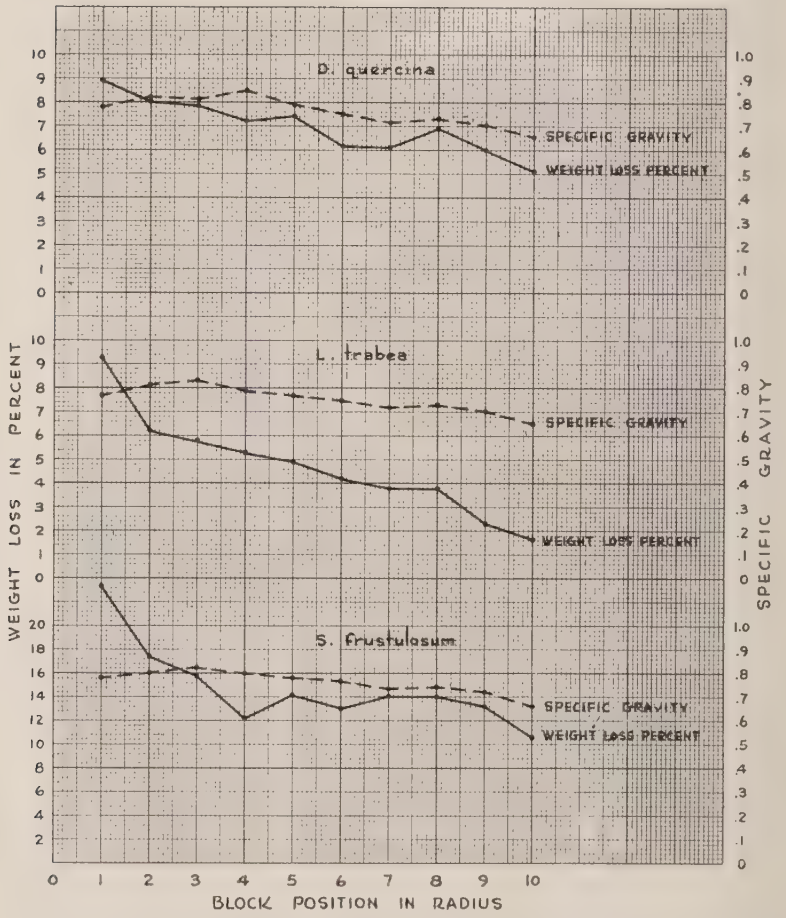

Fig. 6.—The relationships between specific gravity, weight loss, and radial position, as determined by the test fungi for the three trees W1, W2, and W3. Each plotted point is the mean of 6 determinations.

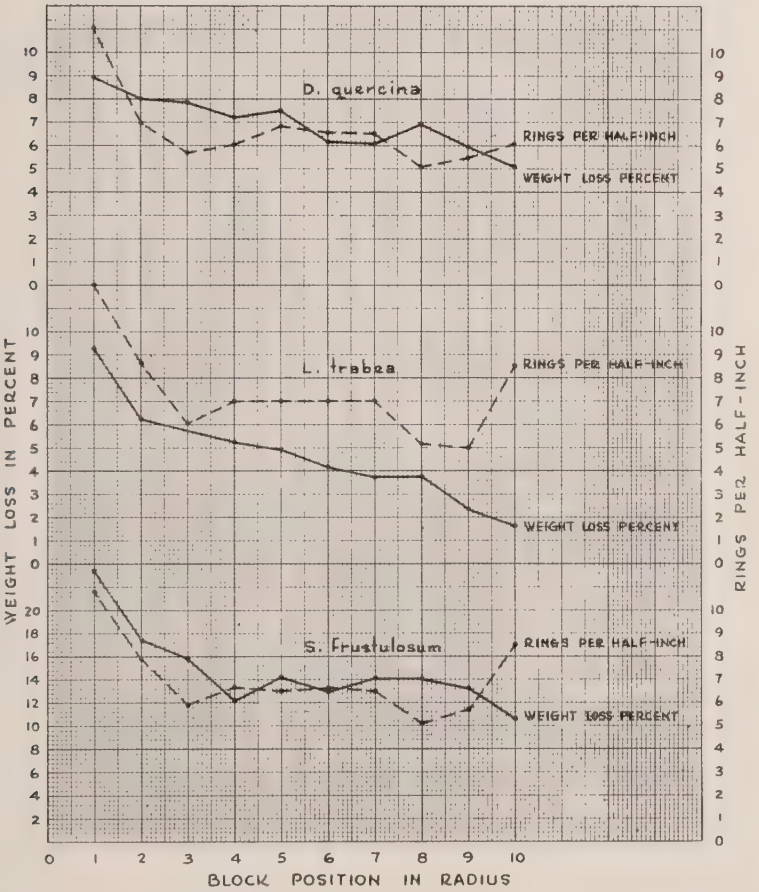

Fig. 7. -The relationships between rings per half-inch, weight loss, and radial position, as determined by the test fungi for the three trees W1, W2, and W3. Each plotted point is the mean of 6 determinations.

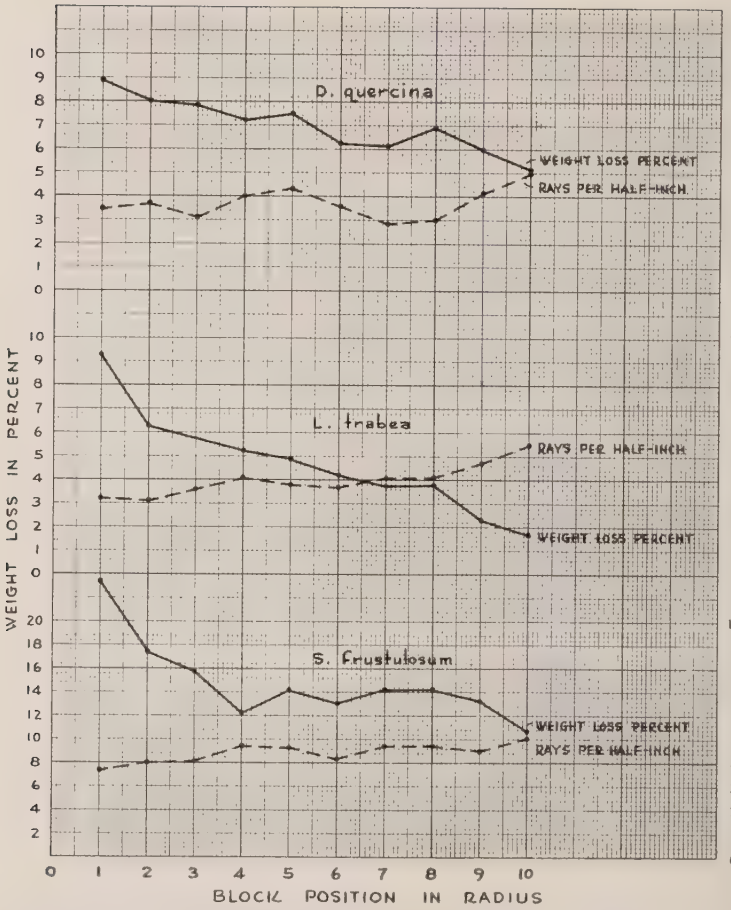

Fig. 8.—The relationships between rays per half-inch, weight loss, and radial position, as determined by the test fungi for the three trees W1, W2, and W3. Each plotted point is the mean of 6 determinations.

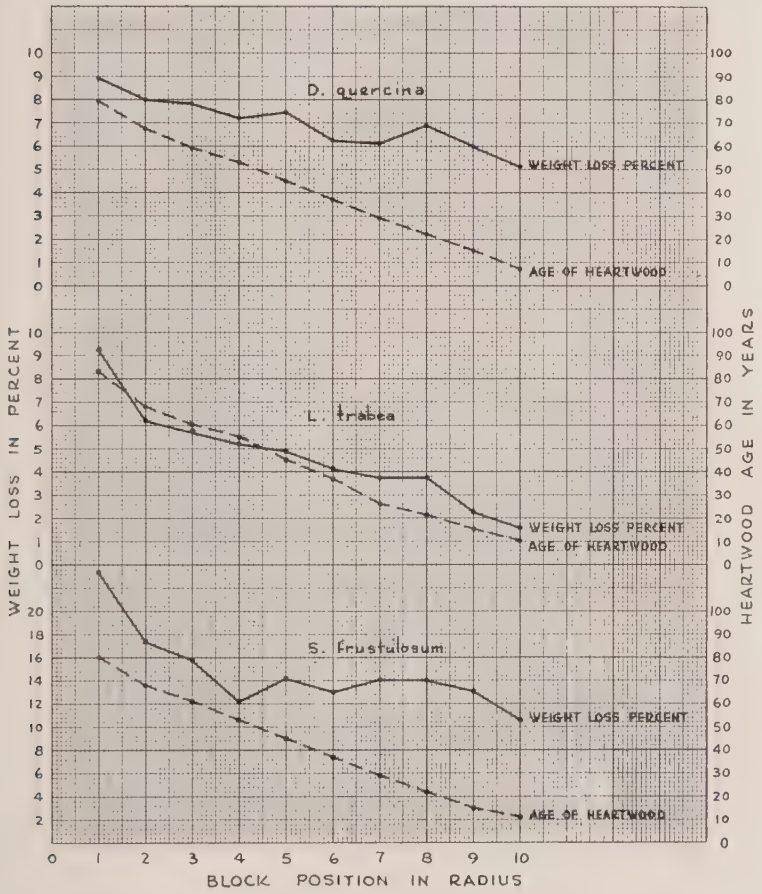

Fig. 9.—The relationships between heartwood age, weight loss, and radial position, as determined by the test fungi for the three trees W1, W2, and W3. Each plotted point is the mean of 6 determinations.

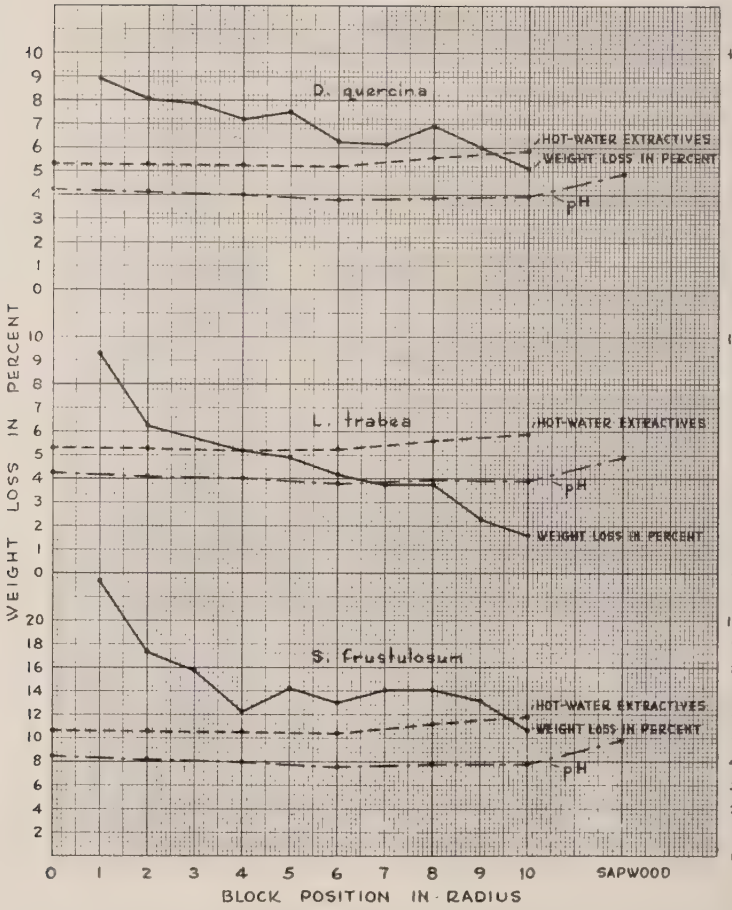

Fig. 10. The relationships between amount of hot-water extractives, pH of the hot-water extractives, and weight loss for the radial positions as determined by the test fungi for the three trees W1, W2, and W3. Each plotted point is the mean of 6 determinations.

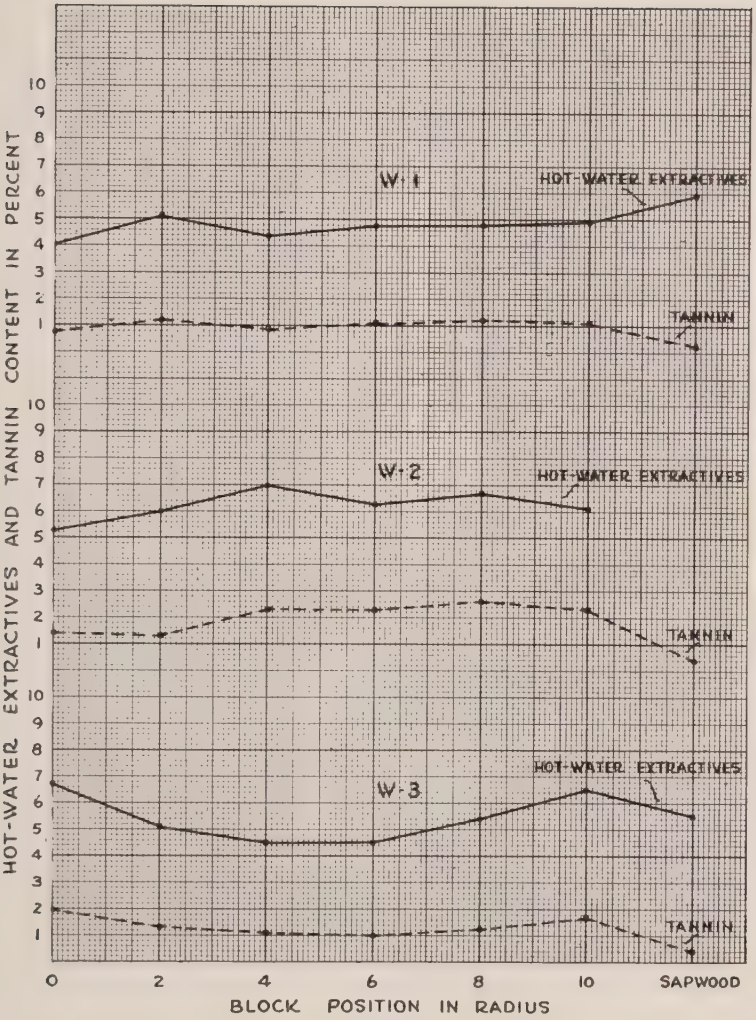

Fig. 11. The relationships between amount of hot-water extractives and tannin content per radial position for each of the trees W1, W2, and W3. Each plotted point is the mean of 2 determinations.

Specific gravity of wood from the various radial positions shows considerable variation throughout the radii of the 3 trees (Fig. 6). In general, low specific gravities were found near the pith and the outer heartwood. High specific gravities were found in the middle position of the radii. Data not presented in this report showed that a decided drop in specific gravity takes place when the sampling position moves from the outer heartwood to the sapwood. With the exception of the pith area a direct relationship is evident between weight loss and specific gravity of the heartwood.

Rings per half-inch per position were found to be lowest in those portions of stems where specific gravity was highest (Figs. 6, 7). In the inner positions of the heartwood a direct relation is apparent between weight loss and rings per inch.

Rays exhibited considerable variation across the radius but in general the number of rays per half-inch increased toward the outer heartwood and there is an inverse relationship between weight loss and number of rays per position in the radius (Fig. 8).

Age of heartwood is directly related to position and therefore is related also to weight loss (Fig. 9).

A slight inverse relation occurred between weight loss and the amount of hot-water extractives per radial position (Fig. 10). However, within the individual trees, this relation is evident only in tree W1. In tree W2 the extractives increased and then decreased with outer radial positions. In tree W3 the extractives decreased and then increased with outer radial position. Of the 3 trees, W2 contained the most hot-water extractives and W1 the least.

The pH of the hot-water extractives gradually decreased both with position and increasing amount of hot-water extractives. The pH of the hot-water extractives raised sharply in the sapwood positions. A color difference also was observed in the extractives from the various positions. Hot-water extractives obtained near the pith were of a deep red color; as the positions approached the outer heartwood the hot-water extractives gradually changed to a light yellow color.

The amount of the tannin from each of the radial positions in the heartwood varied directly with the amounts of the hot-water extractives (Fig. 11). The ratio of tannin to the hot-water extractives was highest in tree W2 and lowest in tree W1. The tannin content of the heartwood was much higher than in the sapwood.

DISCUSSION AND SUMMARY

Specific gravity and rings per inch show direct relationships, with weight loss within the heartwood radius of white oak. Previous studies (22, 51) have shown that a high specific gravity within a species is associated with an increase in decay resistance whereas in this study the reverse is indicated. It is probable that the true effect of specific gravity on decay resistance in white oak is obscured by the more important factors such as amount and toxicity of the hot-water extractives.

Age is directly related to weight loss. This is to be expected because of the direct relationship between age and position in the stem.

Rays per inch is inversely related to weight loss. It may be that this factor is related to age or position; hence its inverse relation to weight loss. However, rays per inch may itself be a factor controlling weight loss. Studies on the chemical composition of white oak rays and total wood reveal that more hot-water solubles were obtained from rays than from other wood elements (23). Tannins are considered also to be largely located in wood rays (48).

A gradual increase in the amount of the hot-water extractives and tannins is apparent in outer portions of the radius, however within individual trees considerable variation occurred (Fig. 11). Inspection of the durability gradients of the trees (Fig. 2 to 4) shows that amount of hot-water extractives and tannins (Fig. 11), can be closely correlated with durability per radial position. However, since similar amounts of hot-water extractives and tannins from different positions in some radii do not impart similar decay resistance, it is evident that an additional factor such as toxicity of the extractives must be present.

Hydrogen ion concentration is closely in accord with amounts of hot-water extractives and tannins, the greater the amount, the lower the pH.

PART IV

STUDY OF THE TOXICITY OF THE HOT-WATER EXTRACTIVES

This phase of the problem includes 3 closely related though separate experiments. Experiment 1 was conducted in order to determine the toxicity of the hot-water extractives in various concentrations. Experiment 2 was designed to discover whether the toxicity of the hot-water extractives in equal concentrations varies with radial position within a tree and between trees. Experiment 3 was designed to determine if removal of tannins from the hot-water extractives affects the toxicity.

MATERIALS AND METHODS

Sources of sample material.—The wood for Experiments 1 and 3 was selected from the outer heartwood of tree W2, and was ground in a Wiley mill until it passed through a medium mesh screen. The hot-water extractives obtained from the 3 trees in earlier phases of the work were used in Experiment 2.

Preparation of hot-water extractives.—All the wood sawdust was placed in beakers within desiccators. When the sawdust reached a constant weight, samples were weighed to within 0.001 gm. and placed in Erlenmeyer flasks for extraction. All oven-dry weights were obtained by calculation from known moisture contents. The methods proposed by Bray (8) to remove the hot-water solubles were used with one modification, namely, the amount of the hot

distilled water used in washing the sample was reduced from 300 ml. to 150 ml.

The amount of extractive in solution was determined from the loss in sample weight due to leaching, that is, the difference between the calculated oven-dry weight and the leached oven-dry weight.

Storage and concentration of extractives.—After extraction all the hot-water solubles were placed in flasks, tightly corked, and stored at 5° C. This was done to limit the activities of contaminants (13) and to reduce possible oxidation (30). All extracts were concentrated and incorporated into malt agar within 10 days. The desired concentrations were obtained by evaporating the extractives under partial vacuum at a temperature ranging between 45° and 50° C. so as to minimize the effects of prolonged heating (49). Concentrations were expressed in percent on a volume basis, *i.e.*, grams of extractive per 100 ml. of solution.

Toxicity tubes.—Soft glass tubes 2.5 cm. in diameter and approximately 20 cm. in length were used in the toxicity tests. Glass dams were formed 3 cm. from the open ends of the tubes so that they retained 10 ml. of agar-extractive solution when lying in a horizontal position (38).

Experimental design.—In Experiment 1, four toxicity tubes were prepared for each of the following concentrations of extractives: 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, and 2.0 percent.

In Experiment 2, four toxicity tubes were prepared for each of the positions along the radii of trees W1, W2, and W3. A concentration of 0.5 percent was selected since the test fungus showed greatest differences in growth rate at this concentration.

In Experiment 3, six toxicity tubes were prepared for each of the following concentrations of extractives: 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, and 2.0 percent. Two of the tubes per concentration were for the unaltered extractives and 4 for the tannin-free extractives.

Preparation of tannin-free extractives.—In Experiment 3 it was necessary to remove the tannins from portions of the extractives. These were prepared from the hot-water extractives by following the basic procedures outlined by Wilson and Kern (46) with modifications described subsequently. Ten grams of hide powder were added to each 200 ml. portion of the extractive solution. The mixture was thoroughly agitated for 5 hours and then filtered through cheesecloth. One-milliliter portions of the filtrate were tested for the presence of tannins with an aqueous solution of 1.0 percent gelatin and 10.0 percent NaCl.

This procedure was repeated until no precipitate was formed upon the addition of the gelatin-salt solution. The extractives were then considered to be free of tannin.

The remaining fixed hide powder was washed to remove all substances adsorbed on the tannin-gelatin precipitate by agitating for 30 minutes in a volume of distilled water equivalent to the original volume of extractives. All washings were repeated until negative

tests were obtained on 1 ml. portions of the filtrate when tested with a dilute solution of $FeCl_3$. All the washings plus the original filtrate were concentrated under a partial vacuum at 45° to 50° C. until the original extractive volume was obtained.

Preparation of culture media for toxicity tests.—Culture media were made by adding malt extract (1.5 percent) and agar (2.0 percent) to proper amounts of extractives to give the desired concentrations. Appropriate amounts of known concentrations of the hot-water extractives were pipetted into the toxicity tubes to make the required concentrations. The media for the tannin-free tests were prepared in a similar manner, using the tannin-free extractives. The media were sterilized by autoclaving for 15 minutes at 10-pounds pressure.

Hydrogen ion concentration measurements.—All measurements of the acidity of the normal extractives and tannin-free extractives were taken with a pH meter as described in a preceding section.

Planting and incubation.—*L. trabea* was selected as the fungus to be used in the toxicity tests since it gave the lowest decay losses in the preceding tests, *i.e.*, it was the most sensitive to the durability mechanism of oak. All culture tubes were planted with a 0.5-cm. square of mycelium cut from the edge of an actively growing culture of *L. trabea*. After planting, all of the cultures were incubated at 30° C.

Growth measurement.—The linear growth of the fungus per day in centimeters was obtained. All the measurements were taken after initial growth had started and subsequent measurements were taken as the differences from these initial growths.

RESULTS

Growth rates of the test fungus, *L. trabea*, were used as a measure of toxicity in the 3 experiments. The growth rates of the fungus were nearly uniform for a given concentration of extractive. The results in these 3 experiments are expressed as the means of the growth rates for the various concentrations and positions at one- and five-day or at five-day growth periods.

In Experiment 1 the mean growth of the fungus on the varying concentrations of the extractive are presented graphically (Fig. 12). The results show that an increase in the concentration of the hot-water extractives caused a marked decrease in the growth rate of the test fungus. This indicates that the hot-water extractives of oak are highly toxic to the fungus. The mycelial characteristics of the fungus varied considerably with the concentration of the extractives. At the higher concentrations the mycelium was sparse, appressed, and deep brown color, while at the lower concentrations the mycelium was abundant, aerial, and a whitish brown color. Abortive sporophores were produced in culture at 2.0 percent concentrations of extractive. Mycelial growth ceased in the 2.0 percent concentration approximately a week after planting.

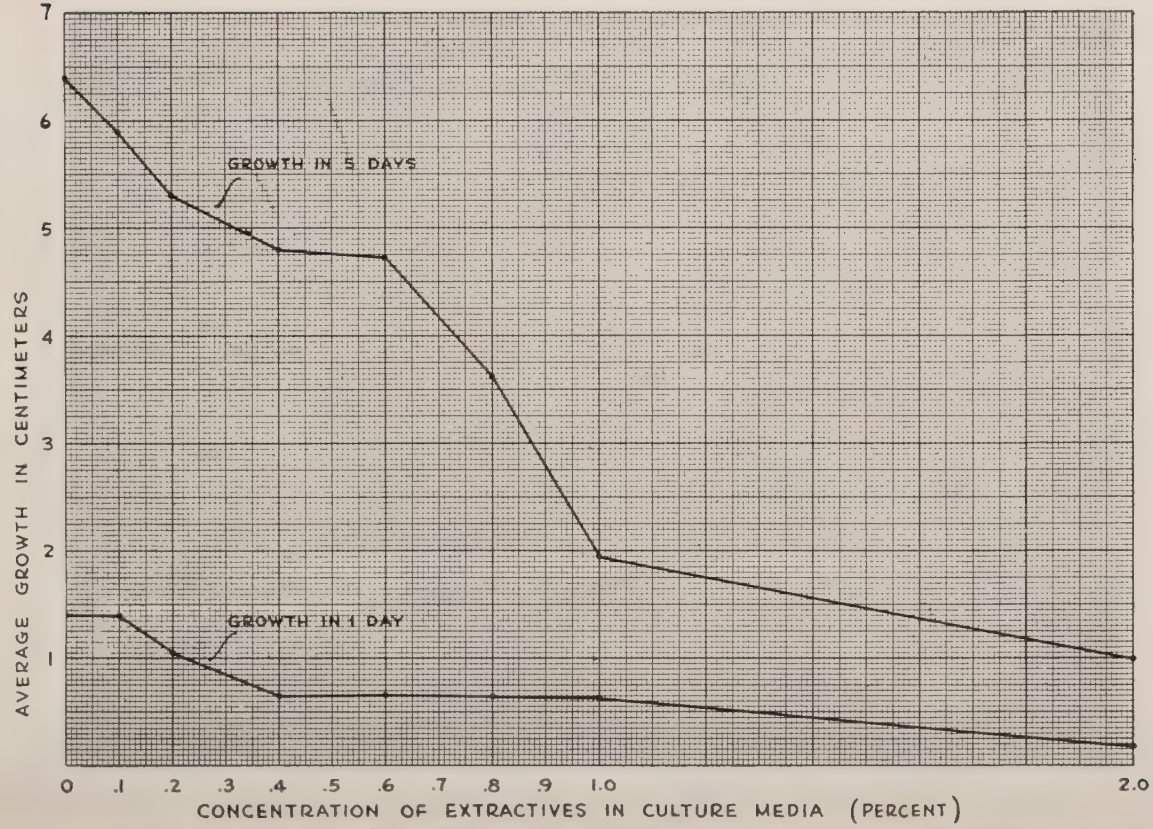

Fig. 12.—The growth rate of *Lenzites trabea* on culture media containing various concentrations of the hot water extractives of white oak, tree W2. Each plotted point is the mean of 4 determinations.

In Experiment 2 the mean growth of the test fungus on equal concentrations of the extractives from the different radial positions of trees, W1, W2, and W3, are presented graphically (Fig. 13). Distinct differences are apparent in the toxicities of the extractives from the various radial positions in the trees. In all cases the toxicity of the extractives increased in the outer portions of the heartwood. The sapwood extractives were much less toxic than the heartwood extractives. Definite differences in the toxicity of the extractives also were apparent between the trees. Of the 3 trees, W1 contained the least toxic extractives and W2 the most toxic. This is in accord with the relative durabilities of the 3 trees determined in the earlier decay tests.

In Experiment 3 the mean linear growth rates in centimeters of the fungus on the various concentrations of the unaltered and the tannin-free extractives are presented graphically (Fig. 14). The difference in the growth rates of *L. trabea* on the malt agar cultures containing varying concentrations of the unaltered extractives and on the tannin-free extractives show that the unaltered extractives were highly toxic. The removal of the tannins from the hot-water extractives of white oak almost entirely eliminated their toxicity.

At 0.1 percent concentrations for short growth periods the tannin-containing extractives stimulated the growth of the fungus, so that it exceeded the growth on the tannin-free extractives (Fig. 14). This stimulatory effect at low concentrations of a toxic material has been commonly observed with fungi (5).

An increase in the concentration of the tannin-free extractives in the culture media had no effect on one-day growth rates and very little effect on the five-day growth rates. These growth rates are practically identical with that of the control or zero concentration of extractives. However, an increase in concentration of the extractives containing tannin in the culture media resulted in a marked decrease in growth rate.

Hydrogen ion measurements of the extractives indicated that the removal of the tannin complex increased the pH of the resulting solution by approximately 1 (Fig. 15). The tannin-free extractives showed only slight differences in pH at the concentration extremes; all intermediate values were identical (Fig. 15). In the tannin-containing extractives an increase in concentration resulted in a gradual decrease in pH.

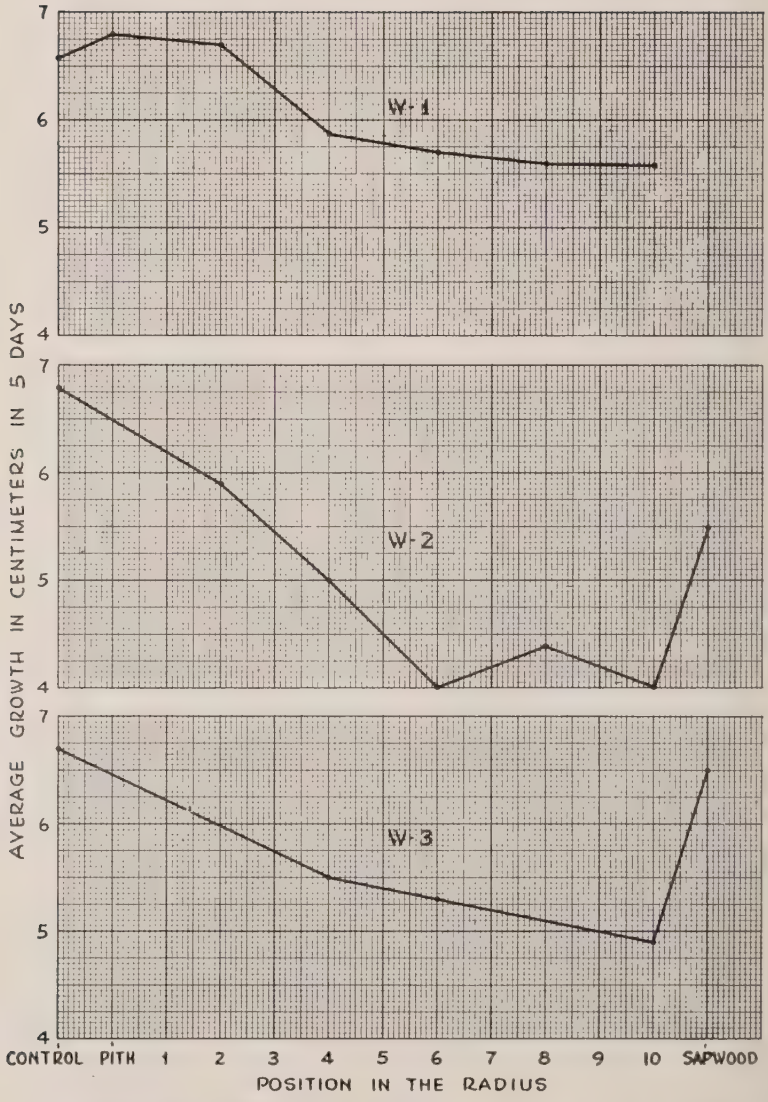

Fig. 13.—The relationships between toxicity of the hot-water extractives and radial positions for trees W1, W2, and W3. Each plotted point is the mean of 4 determinations.

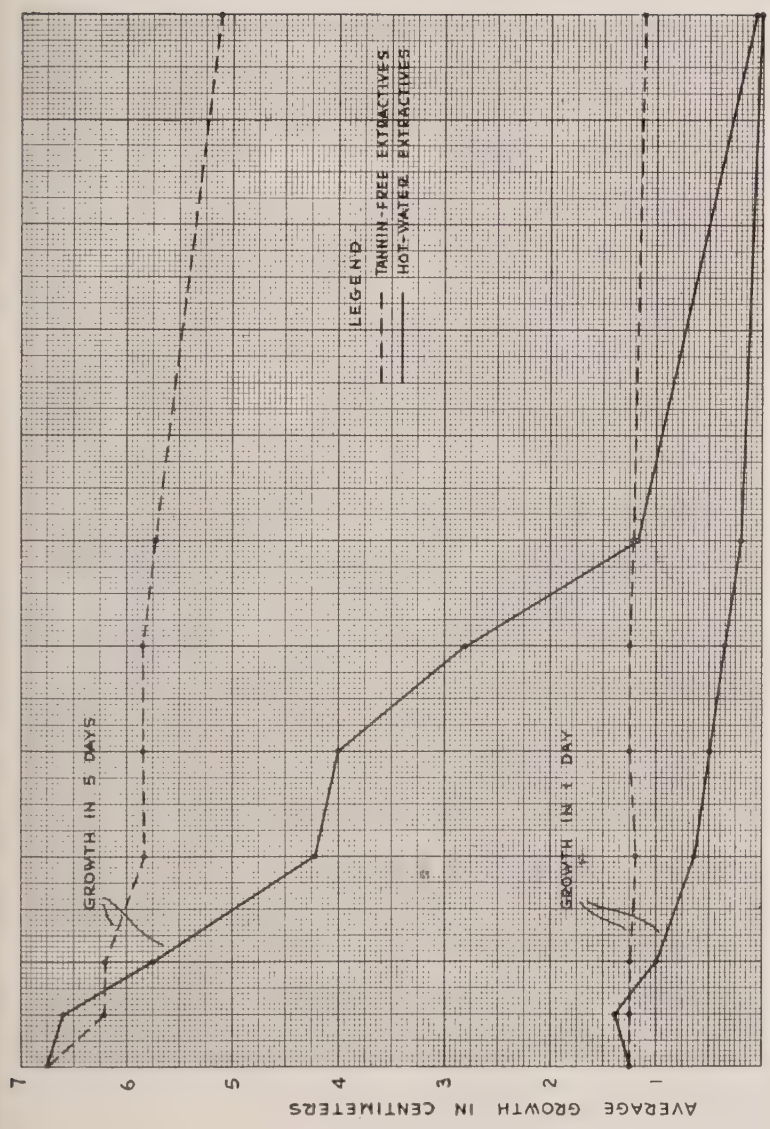

Fig. 14. The growth rate of *Lenzites trabea* in culture media containing various concentrations of hot-water extractives of white oak, tree W2. Each plotted point for hot-water extractives is the mean of 2 determinations. Each plotted point for tannin-free hot-water extractives is the mean of 4 determinations.

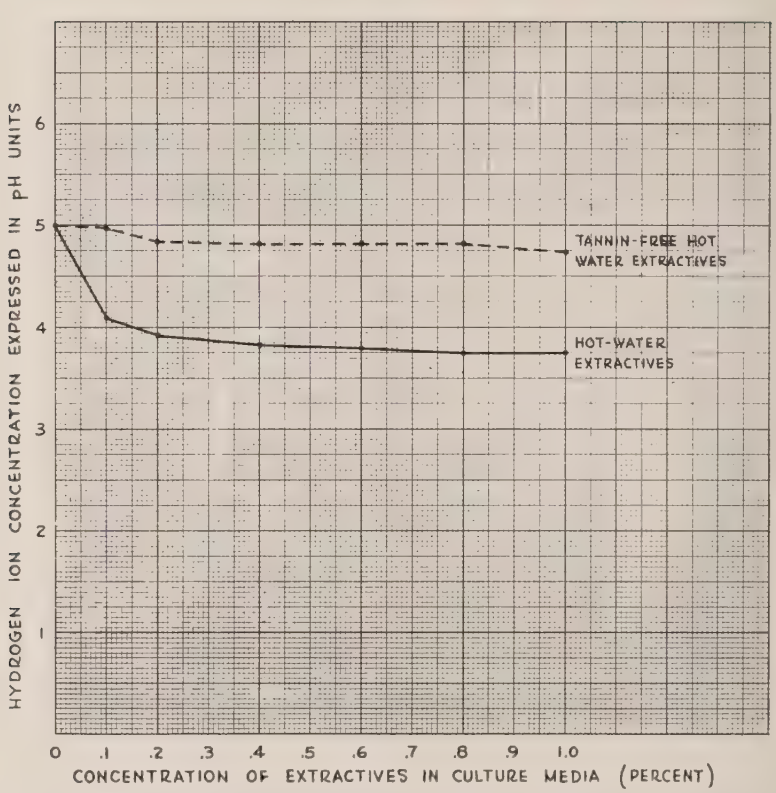

Fig. 15.—The relationship between concentration and pH for the hot-water extractives and the tannin-free extractives. Each plotted point is based on 4 determinations.

DISCUSSION AND SUMMARY

The hot-water extractives of white oak were found to be highly toxic to *Lenzites trabea*, a common wood-destroying fungus. An increase in the concentration of the extractives in culture media caused a decrease in fungal growth. At a concentration of 2.0 percent the hot-water extractives inhibited all fungal activity. The concentration of the extractives found in the heartwood of the 3 white oak trees (Table 10) is more than double this 2.0 percent concentration. This largely explains the durability of white oak.

Distinct differences were found in the toxicity of the hot-water extractives obtained from the various radial positions within the individual trees and between the 3 trees. Considerable variations in the concentration of the extractives are necessary to cause the growth differences that result from variations of toxicity with radial position in trees and between trees (Fig. 13). Within trees the toxicity of the hot-water extractives increased in the outer positions of the radii. This variation in the toxicity of the extractives from

radial positions in the heartwood suggests that a gradual decrease in the toxicity of the hot-water extractives occurs with age. This assumption is further suggested by the progressive color and pH changes in the extractives with radial position and the ease with which tannins oxidize (30, 48).

The variations in the toxicity of the extractives from the 3 trees and the close relationship between toxicity and durability suggests the possibility of using toxicity of the hot-water extractives as an additional index of relative durability in species such as white oak where toxicity of extractives varies more than amount of extractives. In such comparative tests it would be necessary to have the extractives in equal concentrations and from similar positions in the stem.

Striking differences in the growth rate of a wood decay fungus were obtained on culture media containing unaltered extractives and tannin-free extractives (Fig. 14). Even at high concentrations the tannin-free extractives were not toxic. This points strongly to the possibility that the presence of the tannin complex in the hot-water extractive is linked in some way with the decay resistance of white oak.

It is known that hydrogen ion concentration has a considerable effect on the growth rate of many fungi when in culture. The great differences in growth rate of *L. trabea*, on media containing various concentrations of hot-water extractives however, cannot be attributed to variations in pH. A study of the growth of *L. trabea* on culture media at various pH's indicated that only slight variations occurred in growth between the pH range 4.75 to 3.75. Also as shown in Figure 14, it is evident that between 0.0 and 0.2 percent concentrations of the extractive, growth rates were similar for both the tannin-free and the unaltered extractives. The maximum difference in pH of the extractives occurs between 0.0 and 0.2 percent concentration (Fig 15). If pH was the factor which affected fungal growth, then maximum differences in growth would have occurred also at the 0.2 percent concentrations; however, they occur later.

PART V

DISCUSSION AND SUMMARY

The data presented in this paper are based specifically on 3 white oaks. While it is probable that these data apply in general to white oak this can be proven only by studies from a larger sample of trees.

Distinct differences in durability with respect to radial position were found in the white oaks. Increased resistance to decay occurred progressively from the pith through the outer heartwood.

Proof of the differences in durability of white oak makes it possible to utilize the wood more effectively. For example, under conditions which are favorable to decay, oak timbers containing boxed-in heartwood should not be used because of the low resistance of the wood close to the pith. The service life of white oak fence posts can be lengthened by splitting the larger logs and eliminating

the non-resistant wood. Plywood selected from the outer heartwood cylinder of white oak will be the most resistant to decay where durability is a factor, such as plywood staves in casks of various kinds.

The decay and toxicity studies indicate that important durability differences occur between the trees as well as within the heartwood cylinder of a single tree. This information is important to forestry practice because highly resistant trees can be detected and can then be propagated by cuttings.

In the past, relative durabilities of trees have been determined by lengthy laborious decay tests. Simple, short techniques are needed to ascertain relative durabilities. These studies indicate that relationships occur between certain physical and chemical properties of oak wood and its decay resistance. Within trees, relationships were found between durability and position in the stem, specific gravity, rings per half-inch, age, number of rays per half-inch, amount and toxicity of hot-water extractives, and amount of tannins. Tannin content of the wood at various radial positions was found to vary directly with amounts of the hot-water extractives. Of these factors, toxicity of hot-water extractives, the amount of hot-water extractives, and amount of tannins were indicative also of differences in durability between trees. Of these factors the amount and toxicity of the hot-water extractives can be easily determined in short periods of time.

In order to determine the relative durabilities of oak, it is suggested that comparative tests be made to determine both the *amount* of the hot-water extractives and the *toxicity* of the extractives in known concentrations from similar positions in the outer heartwood. The most favorable concentration of these extractives in culture media for such tests was found to be 0.5 percent.

White oak was found to have hot-water extractives that were highly toxic to a common wood-destroying fungus. These hot-water extractives of oak are present in the heartwood in amounts sufficient to hinder fungal growth. The toxicity of the hot-water extractive in white oak was shown to vary with radial position. It is probable that decay resistance is the result of both the amount and the toxicity of the hot-water extractives in the oak wood. Within the radii of trees greater variation occurs in the toxicity of the extractives than in amount of extractives.

Studies on the toxic materials in the hot-water extractives indicate that they belong to the tannin complex. The removal of the tannins from the hot-water extractives eliminated their toxicity to fungi in culture on agar media.

While this is strong evidence that the tannins are probably responsible for the durability of white oaks, the method of investigation has certain limitations. It is not known whether the agar containing the dispersed extractive is at all comparable to the extractives in wood. Also, it is not known whether extractives are altered in separation from the wood. However, these results suggest that the tannins exert toxic effects on fungi growing in white oak.

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